Suppression of Hadroproduction in Nuclei*

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Abstract

We argue that nuclei are not transparent for fast projectile partons. Color transparency is effective for final state interactions in heavy particle production, though nuclear filtering of initial partons can reduce the cross sections. We show that short-ranged initial state interactions, which have been neglected so far, can be important in hadroproduction. With the present scenario of hadroproduction a qualitative discription of data can be obtained.

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1. Introduction

The data for hadroproduction on nuclei contradict the standard model of color transparency (CT): the suppression of J/ψ- and Υ- production in nuclei[1] is far beyond the predictions of standard CT model. The observed large distortion of p_T-distributions in all hadroproduction reactions in nuclei, especially in Drell Yan (DY) production, can hardly be described without the contribution of initial state (IS) interactions. In some papers the elastic IS interactions have been taken into account to explain the p_T-dependence (see, e.g., Refs.[3, 4]). We show that the hadroproduction suppression in nuclei can be attributed to short-ranged IS interactions of projectiles, which have been neglected so far. We argue that these interactions do not contradict the CT forecasts and that CT is not very effective for projectile partons.

According to CT forecasts, the propagation of a color singlet partonic configuration in nuclei is described by cross sections vanishing like r^2, where r is the configuration transverse size[2]. Though this result was first obtained within the Low-Nussinov model, it has a plausible physical interpretation and got a larger application. A simple analog is the non-interaction of photons with point-like dipoles. Heavy quarkonia are first produced as bare singlet quark-antiquark configurations with $r \sim 1/Q$ and further hadronize and get a normal hadronic size far outside the nucleus. Therefore the final state interactions for heavy quarkonium production in nuclei are unimportant. The situation with IS interactions is quite different. Many authors argued that only small size projectile parton configurations are involved in the annihilation with large Q^2 (see,e.g., Ref.[5]). In fact, the annihilating (and produced) partons must have the transverse separation $\sim 1/Q$. But the annihilating partons belong to different hadrons (projectile and target), while the produced partons belong to the same hadron (or pre-hadron). There is no restriction for transverse separation between partons from the same projectile hadron and the closeness of annihilating partons has no effect for the propagation of projectile hadrons in nuclei. Therefore large size partonic configurations of projectile hadrons could contribute to hadroproduction as well, but these configurations are filtered out by the IS nuclear filtering and the hadroproduction on back nucleons is less effective. The above argumentation is not valid for elastic formfactors since

in this case only small partonic configurations of the size $\sim 1/Q$ from both initial and final hadrons can contribute. This is so because all partons must correlate during the time $\sim 1/Q$ in order for the reaction to be elastic. But only one active parton can participate in inelastic reactions and other projectile partons have no knowledge of what happens with that parton.

2. Initial state interactions.

Several authors[6, 7] demonstrated the cancellation of IS gluon exchange diagrams in hadroproduction on nuclei at large Q^2. The contribution of exchange gluons is shown either to vanish or, for colliniar gluons, to enter the familiar structure functions[8, 9]. We now focus on the contribution of active - spectator IS interactions with sufficiently large exchange momenta (see below). Assume that the operators Q_1 and Q_2 describe the IS interactions and the final annihilation of a projectile parton, resp., $|i >$ is the assymptotic initial state and $|f >$ is the final state after the interaction Q_2. We neglect other interactions of the parton. The vanishing of Feynman diagrams describing the two-step process, i.e. the annihilation after the IS scattering, means that

$$< f|Q_2 Q_1|i >= 0. \tag{1}$$

For hard IS interactions, this equation is justified because the transverse momentum of an active parton after the IS interaction is assumed to be larger than the typical transverse momentum of annihilating partons[7]. Many authors concluded that the interaction Q_1 can be neglected if (1) is valid. This would be correct if particle fields were infinite (remember that Feynman diagrams describe interactions of infinite fields) and particles could interact at any space-time point. In this case we could use the same assymptotic initial state $|i >$ for both interactions Q_1 and Q_2. In reality, particles are localized objects and assymptotic initial states for front and back nucleons can be different. We assume that the interaction Q_1 is short-ranged, i.e. for any momentum l involved in this interaction

$$l \gg L^{-1}, \tag{2}$$

L is the target length in the lab. frame. This equation is our definition of hard interactions. The interaction Q_2 is also short-ranged at large Q^2. In this case the de-excitation time (or the

coherence length) of the projectile hadron is unimportant because this parton participates either in Q_1 or in Q_2 interaction, but not in both interactions due to (1). The second step of the process is described by the amplitude $< f|Q_2|i' >$, where $|i' >$ is the assymptotic initial state for the interaction Q_2,

$$|i' >= C|i > + \sum_n |n > < n|Q_1|i >, \qquad (3)$$

$|n >$ are final states after the interaction Q_1. Note that $|i' >$ is the assymptotic state for the interaction Q_2 only under the condition (2), when the interactions Q_1 and Q_2 are independent. Eq. (1) can now be rewritten as

$$< f|Q_2|n >= 0. \qquad (4)$$

If the states $|n >$ and $|i >$ are orthogonal, and this is a reasonable assumption for hard IS interactions, then the probability conservation demands

$$< i'|i' >=< i|i >= 1, \ \ C^2 = 1 - \sum_n | < n|Q_1|i > |^2. \qquad (5)$$

For hard IS interactions, the condition (4) can be fulfilled indeed. In this case the whole reaction is described by the amplitude

$$< f|Q_2|i' >= C \ < f|Q_2|i > . \qquad (6)$$

The macroscopic factor C describes the probability to escape hard IS interactions. Note that the interaction Q_1, which is responsible for this factor, contains the lowest powers of α_S. For soft IS interactions with $l \sim L^{-1}$, the result (6) is not correct because in this case $|i' >$ is not an assymptotic state for the interaction Q_2. In this case the results of Refs.[6] -[9] for soft gluons should be applied instead. In Refs.[7, 9] the following target-length condition for the validity of factorization was obtained

$$Q^2 \gg x_q LM l_T^2, \qquad (7)$$

where x_q is the projectile parton's Bjorken variable, M is the target mass and l_T is the exchanged gluon transverse momentum. From the derivation of this condition it follows that

for hard IS interactions, (7) can be interpreted as a condition for the validity of (4). In fact, if (7) is fulfilled then the only remaining contribution of IS interactions to the two-step amplitude comes from colliniar gluons [8, 9]. As we have shown, in this case the factor C suppresses the hadroproduction cross sections, provided the target-length condition (2) is satisfied.

It was argued[8] that hard IS interactions cannot take place because in the c.m. frame projectile and target partons remain space-like separated until the final annihilation takes place. In fact, in that frame the nucleus is viewed as a thin pancake due to Lorentz contraction, whereas the wave-lengths of projectile partons are finite and larger than in the target rest frame. At certain energies, the wave-lengths become larger than the contracted nucleus length and the condition (2) is not satisfied in the c.m. frame. However, the wave-length (and uncertainty principle) argumentation should be used with more care in fast moving frames. This can be illustrated by the following example. Assume that in the target rest frame a projectile (or exchanged) particle, which directly couples to target particle fields, has the four momentum $p = (E, \vec{P})$ and the longitudinal separation between two target particles is L. In this frame the target system is well described by the instant-form dynamics and we may say that these two target particles are separated by the space-time interval $\xi = (0, 0, 0, L)$. The invariant macroscopic target-length condition can be obtained from the requirement that the phase accumulated by the fast particle on the interval ξ is sufficiently large,

$$p\xi \gg 1. \tag{8}$$

In this case local interactions of the fast particle with two target particles will be independent. In the target rest frame, this condition takes the form (2), which is non-relativistic with respect to the target. But it is misleading to use (2) instead of (8) in fast moving frames. In such frames a composite system cannot be unambigiously described by the instant form wave functions and the relative position of two target particles at the same time is not well defined. For the relativistic description of composite systems in fast moving frames it is more appropriate to use the light-cone formalism[10], in which all systems are described at

fixed light-cone "time". In this formalism a transition from one frame to another, as well as a composite system description in fast moving frames, is unambigious. Note that there is no Lorentz contraction of a target light-cone "size" measured at a fixed light-cone "time" in the c.m. frame. A more detailed discussion of this problem is beyond the scope of this paper. From the invariant condition (8) it follows that if two target particles are separated for a projectile in the target rest frame, they are also separated in any other frame. Otherwise cross sections for composite targets would not be invariant values. The cross section of, say, photon scattering from a dipole would be frame-dependent because the relation between the photon wave-length and the dipole size depends on the choice of frame. For very energetic photons, this would lead to the vanishing of photon-dipole cross section in the c.m. frame due to Lorentz contraction of the dipole size. In reality, high momentum photons interact almost independently with dipole charges.

We conclude that there is no theoretical evidence to ignore hard IS interactions in hadroproduction on nuclei. Note that our conclusion does not contradict either the factorization theorem for one-nucleon target, because in this case $|i' > \approx |i >$, or the "weak" factorization theorem[8, 9] for nuclear targets, because the factor C only changes the normalization of the amplitude and the annihilation vertex is described by the same factored form. In Ref.[11] it was suggested that the hadroproduction suppression should be attributed to energy loss of incident partons in nuclei. However, the energy loss needed to explain the data is too large [12], if the same active parton is going to annihilate afterwards. In contrast to Ref.[11], we assume that some IS interactions cannot be followed by the annihilation of the same active parton. In our conjecture, IS interactions reduce the flux of partons, which are suitable for hadroproduction. The contribution of these IS interactions cannot be included in target or projectile hadron structure functions. These structure functions contain diagrams with deep inelastic interactions of active partons, while the factor C does not.

3. Numerical results.

To simulate hard IS interactions, we introduce the phenomenological parton-nucleon absorption cross section σ_{abs}. We assume that these interactions are approximately the same for quarks and antiquarks, $\sigma_{abs}^q \approx \sigma_{abs}^{\bar{q}}$. It is appropriate to find σ_{abs}^q from the Drell-Yan (DY)

production by pions. This reaction probes the quark content of a target and is not affected either by final state interaction or by the possible excess pion contribution. The ratio of nuclear and nucleon cross sections for this reaction, $R^\pi_{DY}(x)$, and the electroproduction cross section ratio, $R_{EMC}(x)$, are connected by the equation

$$R^\pi_{DY}(x) = F\ R_{EMC}(x). \tag{9}$$

The factor F, which is the generalization of the macroscopic factor C^2, can be written in the eikonal form

$$F = \frac{1}{A\sigma_{abs}} \int d^2b\,(1 - e^{-\sigma_{abs}\,T(\vec{b})}), \tag{10}$$

$T(\vec{b})$ is the profile function (we assumed $\sigma_{abs} \gg \sigma_{DY}$).

The data[13] show that in accordance with (9) the ratio $R^\pi_{DY}(x)$ is systematically below $R_{EMC}(x)$, whereas their x-dependences are quite similar (see Fig.1). The value $\sigma^q_{abs} = 2mb$ gives a reasonable fit for the $E_\pi = 140$ GeV data, while $\sigma^q_{abs} \approx 1.5$ mb would better fit the combined data. Note that the data for $E_\pi = 286$ GeV have larger error bars and do not demonstrate a smooth behaviour. In reality, σ_{abs} may be x- and p_T- dependent. Therefore the constant parameter σ_{abs} can only reproduce the bulk of the suppression.

It is usually accepted that the main subprocess for the quarkonium production is the annihilation of projectile and target gluons. In this case σ^g_{abs} describes the gluon-nucleon IS interactions. In Fig.2 the CT model predictions[14] for the J/ψ and Υ production are compared to the data and we can see that the standard CT scenario is not good enough. There were many attempts to explain this discrepancy. Among them, we can mention two possible explanations: the gluon shadowing in target nuclei[15] and the final state interaction of produced heavy quarks[16]. There is no final agreement what is the origin of parton shadowing, which have been observed in deep inelastic lepton-nucleus scattering at small x. Therefore it is not clear whether the same shadowing should take place at time-like Q^2. The gluon shadowing cannot entirely explain the quarkonium production suppression for the following reasons: 1) the Υ-production is also suppressed though the measured x-region in this case[1] does not correspond to the shadowing effect; 2) it is hard to explain the different magnitude of nuclear suppression in DY production by pions, in DY production by protons,

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in J/ψ-production and in Υ-production. At most, the parton shadowing is not the only source of hadroproduction suppression. The additional final state interactions of quarkonia, that are not included in the standard CT model, can hardly explain the suppression for the following reasons: 1) the observed suppression of ψ'-production is the same as the suppression of ψ-production, though the transverse size of valence parton configuration is much larger in the first case; 2) the suppression of J/ψ-production by photons is not so large[17], which means that the suppression is due mainly to IS interactions.

According to our conjecture, the production cross section ratio for this reaction, R_Q,can be written as

$$R_Q = F R_Q^{CT}, \qquad (11)$$

where R_Q^{CT} is the standard CT result for the ratio and the factor F describes hard IS interactions of projectile gluons. As it follows from Fig.2, the best fit of data is with $\sigma_{abs}^g(J/\psi) \approx$ 4 mb and $\sigma_{abs}^g(\Upsilon) \approx 2$ mb.

The cross section $\sigma_{abs}=$ 1.5 - 4 mb provides an overall description of hadroproduction data. From the comparison with the data it follows that 1) $< \sigma_{abs}^g > \approx 2 < \sigma_{abs}^q >$ and 2)$\sigma_{abs}^g(J/\psi) > \sigma_{abs}^g(\Upsilon)$. The first result can be explained by the color factors which make the gluon-nucleon cross section twice as large as the quark-nucleon cross section. The second result could be explained, for example, by the contribution of non-fusion mechanism of charm production[18] or by the contribution of quark-antiquark annihilation subprocess to the bottomonium production. Both mechanisms make the IS nuclear effects in J/ψ-production larger than in Υ-production. However, the data for diffractive charm production[19] do not support the non-fusion mechanism of J/ψ-production. Note that the J/ψ-meson is probably too light for the validity of factorization. The factorization condition (7), which can be rewritten as

$$Q^2 \gg 0.25 \, A^{2/3} GeV^2, \qquad (12)$$

is fulfilled for Υ-production and, partially, for DY reactions, but not for J/ψ-production. This is a possible additional source of nuclear effects in the last case. And, finally, the Sudakov suppression of color correlations[6, 7] is not very effective for J/ψ-production because

in this case the Sudakov formfactor is not so small, $|S(Q^2)|^2 \sim 1/3$ at $Q^2 = 10 GeV^2$. This should also make nuclear effects in J/ψ-production larger than in Υ-production. With all these remarks, the suggested suppression mechanism gives a satisfactory phenomenological description of the data.

In the DY production by protons, which probes the antiquark content of a target, the measured cross section ratio is close to 1 [20]. Therefore many authors concluded that there were no excess pions (sea enhancement) in nuclei. This would be correct in the absence of IS interactions. In Ref.[21] it was shown that the contribution of a typical amount of excess pions, ~ 0.1 pions per nucleon, is roughly compensated by IS interaction with $\sigma_{abs}^q \approx 2mb$. This means that the models for the nuclear EMC-effect, assuming some pion excess in nuclei, are rather supported by the DY production data than ruled out as many authors concluded. An indication of pionic contribution to the DY production by protons could be the data for the angular distribution of leptons, which has an important $sin^2(\Theta)$-term for πN collisions. Following our conjecture, there is an additional source of the relative enhancement of hadroproduction with large p_T: projectile partons from small size configurations have larger p_T than partons from large size configurations, which are filtered out by IS interactions. This effect will be considered elsewhere.

We conclude that the CT model can describe the available data for hadroproduction on nuclei, provided the IS interactions are taken into account. The J/ψ-production suppression in heavy ion collisions could be a signal of quark-gluon plasma. Here we considered a new source of nuclear suppression of hadroproduction. A firm conclusion about the observation of quark-gluon plasma cannot be made without determining all major nuclear effects in hadroproduction.

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Figure captions.

Fig.1. The ratio $R_{DY}^{\pi}(x)$, calculated for Fe with $\sigma_{abs}^{q} = 0$ ($R_{EMC}(x)$, dashed curve), 2mb (solid curve) and 4mb (dotted curve). The data are for the DY production by pions measured on W and D at $E_{\pi} = 140$ GeV (dots) and $E_{\pi} = 286$ GeV (circles) [13].

Fig.2. The ratio R_Q for the quarkonium production calculated with $\sigma_{abs}^{g}=0$ (R_Q^{CT}, dashed curves), 2mb (solid curves) and 4mb (dotted curves). Upper curves are for Υ and lower curves for J/ψ production. The data for Υ (dots) and J/ψ (circles) production by protons are from Ref.[1].

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